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Improved Modelling of Trains Braking Under Low Adhesion Conditions

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Abstract

Predicting the behaviour of trains when braking under low adhesion conditions presents considerable challenges. This paper describes an approach to the problem using a model of the full train braking system known as LABRADOR (Low Adhesion Braking Dynamic Optimisation for Rolling Stock) and an improved method for representing the creep force – creepage behaviour when low adhesion is present known as WILAC (Water Induced Low Adhesion Creep Force Model). The development of these models and their integration are summarised and a number of test cases are presented to demonstrate the improvements which can be gained from this approach. A number of suggestions are made for future enhancements with the aim of providing brake engineers and systems integrators with reliable simulation tools for optimising train braking performance when low adhesion is present.

Keywords: train braking, low adhesion creep force model; brake model; wheel slide protection, braking simulation

1 Introduction

Low adhesion in the wheel/rail interface can cause both safety and performance issues. In braking it can lead to station overruns and signals passed at danger (SPADs) and in traction it can lead to costly delays. It can also cause damage to wheel (flats) and rail (burns, white etching layer). Low adhesion can result from a number of causes including “wet-rail” syndrome, where a mixture of a small amount of water and oxide causes friction to lower; leaves, oil, etc. A lot of attention has been paid to understanding and mitigating against leaf problems, “wet-rail”, however, has received less attention. In previous work a validated creep force model (Water Induced Low Adhesion Creep Force model (WILAC)) was developed for predicting the effects on adhesion of small amounts of water in the wheel/rail interface (Trummer, et al., 2017). The aim of this work was to implement the WILAC model in the recently developed train braking model (Low Adhesion Braking Dynamic Optimisation for Rolling stock model (LABRADOR)) (Alturbeh, Stow, Tucker, & Lawton, 2018) to improve the low adhesion input and therefore braking predictions for a “wet-rail” scenario. An improved model will help in developing new braking strategies; new brake designs and different mitigation products.

2 LABRADOR

The LABRADOR model has been developed in MATLAB/Simulink software. The model has been developed to represent the complex behaviour of modern multiple unit passenger trains braking in normal and low adhesion conditions. It is modular to allow easy specification of vehicle, bogie and wheelset subsystems. Figure 1 shows a block diagram of the LABRADOR model in which the train module interacts with the environment model and driver brake demand model as inputs. In LABRADOR’s modular structure the train module contains one, two, three, or four functionally identical vehicle modules, each vehicle module contains a number of functionally identical wheelset modules. Within the wheelset module, wheel slide protection (WSP) (an automatic system used to detect and prevent wheel slides during braking or acceleration) and friction braking, sanding, dynamic braking, and wheel and contact patch subsystems exist. The contact patch module contains the contact patch temperature, contact patch dimension and adhesion creep curve modules. The following subsections summarise the functions of the train brake system modules.

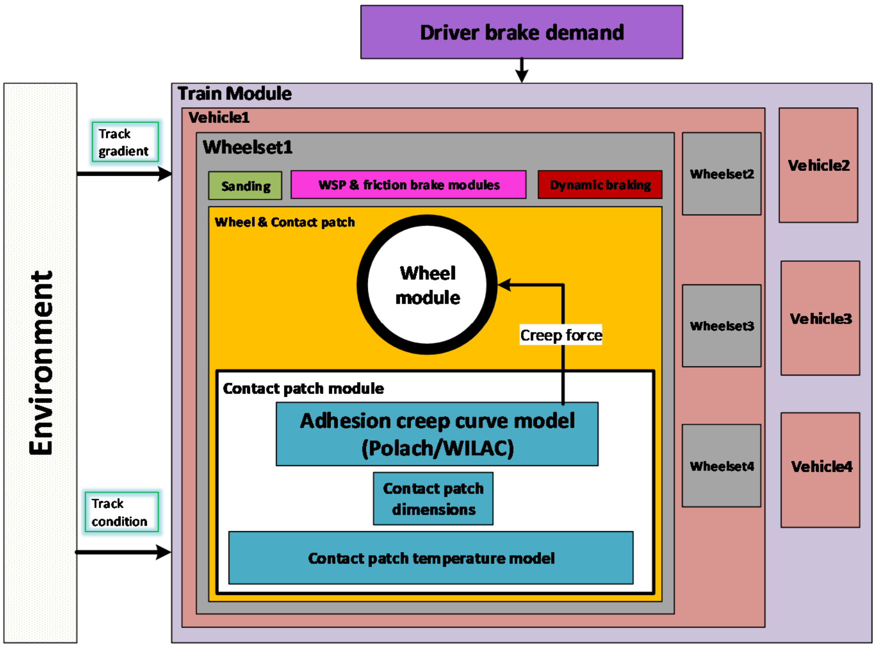

Figure 1 LABRADOR model architecture for 4 car train

Train module:

The train module:

(1) Calculates the drag forces as a consequence of train speed and train gravitational forces using gradient data from environment module;

(2) Computes train acceleration, speed and position as a consequence of the drag, gravitational and wheel-rail forces (including mass and inertia terms) applied to the train;

(3) Allocates drivers brake demand, between each vehicle, according to the state of brake equipment on the vehicle (dynamic brake isolation, WSP activity etc.).

Vehicle module:

The vehicle module:

(1) Allocates vehicle brake demand as a combination of friction brake demand and dynamic brake demand to each wheelset, depending on the state of the vehicle's brake equipment;
(2) Calculates the load transfer due to train acceleration, wheel-rail forces and track gradient.

Wheelset module:

The wheelset module groups a number of modules, that are:

(1) Sanding module
(2) Wheel Slide Protection (WSP) and friction brake module
(3) Dynamic braking module
(4) Wheel and contact patch module

These modules are contained within the wheelset module because their actions are exclusively centred on one individual wheelset. The wheelset module has no specific function; it exists to contain the modules listed above and to receive certain data from the vehicle module, such as friction brake demand, electrodynamic brake demand and train/vehicle speed and pass it to its inner modules.

Sanding module:

Sand is applied to the wheel-rail contact patch when wheel slide exceeds a certain level. The WSP and friction braking (WSP&FB) module monitors wheel slide and signals to the sander module to increase adhesion, subject to a time lag. The sander module tells the contact patch module that input adhesion is increased. A simple model developed by (Lawton, 2017) has been used to calculate the change in adhesion due to sand at each wheelset. The model is based on two parameters; adhesion boost from sand and residual sand ratio:

- Adhesion boost from sand is the adhesion increase generated at the first wheelset to pass over newly applied sand.
- Residual sand ratio is the ratio of adhesion at one wheelset relative to adhesion at the preceding wheelset and is used to represent the diminishing effect of sand on adhesion at each successive wheel.

Both of these parameters vary with the rate at which sand is discharged. In LABRADOR a constant sanding rate of 2 kg/min is considered in which the adhesion boost from sand is about 0.06 and the residual sand ratio is 50%. However, the user can configure these values with other sanding system parameters via the GUI.

WSP and friction brake module:

The activities of the WSP and friction brake (WSP&FB) are closely linked, hence, they are modelled as a single module. The WSP&FB module controls braking and sanding as a consequence of wheel slide. The module:

(1) Receives wheel rotational acceleration and speed from the wheel module;

(2) Calculates wheel slide using the actual wheelset rotational speed, wheel radius and the chosen train speed;

(3) Controls friction brake torque taking into consideration delays in the pneumatic system.

(4) Activates wheelset sanding and isolates the electrodynamic brake, depending on wheel slide;

(5) Describes the state of the brake equipment (dynamic brake enabled/disabled, friction brake on/off, sanding on/off) to the vehicle module for use in setting brake demands.

Electrodynamic braking module:

The electrodynamic brake module produces a torque on the wheelset. This brake can be disabled if wheel slide is excessive; electrodynamic brake torque is then zero until the train stops. The electrodynamic brake torque is proportional to the electrodynamic brake demand, and there is negligible delay between changes in electrodynamic brake demand and electrodynamic brake torque.

Wheel and contact patch module:

The wheel and contact patch module consists of the wheel module and the contact patch module.

***Wheel module*:**

This module simulates the rotational behaviour of the wheelset, depending on the electrodynamic and friction brake torques, the wheel load and the contact patch behaviour. The wheel module will:

(1) Calculate drag force for the wheelset;

(2) Calculate gravitational force (including mass and inertia terms) for the wheelset;

(3) Calculate the force demand on the wheel-rail contact point and relate gravitational force (including mass and inertia terms), drag force, friction brake torque and dynamic brake torque (the force demand on the contact point) and available wheel-rail force to calculate wheel rotational acceleration and speed.

Contact patch module:

The contact patch module is formed from the following modules:

(1) Polach module: The creep curves and creep force are calculated based on the Polach approach (Polach, 2005).
(2) WILAC module: WILAC approach is used to calculate the creep force.
(3) Select block: The creep force is generated as a result of interaction between the wheel and rail at the contact patch. This block is used to switch between the WILAC and Polach models.
(4) Contact patch temperature module: estimates the temperature of the contact patch based on the Tanvir model (Tanvir, 1980).
(5) Contact patch dimensions block: The dimension of the contact patch is calculated based on an approximated Hertzian model (Antoine & C Visa, 2006).

Environment module:

The environment module provides all of the external data required by the train modules and:

(1) Passes the initial conditions for train position, train speed to the train module
(2) Takes in data from the contact patch modules on the adhesion/water amount behind the wheelset, updates the adhesion\water amount map and, knowing wheel positions within the train, provides data to the contact patch modules on incoming adhesion/water amount for each wheelset
(3) Provides gradient information to allow calculation of gravitational forces by the train or vehicle modules.

It is worth mentioning here that the current version of LABRADOR is limited to simulate trains running on straight line. Hence, track curvature and cant are not considered as to be part of the model inputs.

Driver's brake demand model:

The driver brake demand model mimics a standard 4-step brake controller; notch 1, 2, 3 and Emergency, corresponding to values of train brake demand of 3%, 6%, 9% and 12% of g (gravitational acceleration $g = 9.81$ m/s^2). The driver's brake demand model can generate constant and variable (pre-defined profile) values of driver brake demand.

The modular structure of the LABRADOR provides the easiest way to exploit the duplicated systems within real, long trains. For example, changing how the WSP system works for every vehicle in a 4 car train only involves changing the WSP module which is then replicated many times within the model structure for a long train. Figure 2 illustrates the functions within the simulation tool. One to four car trains can be constructed with configurable brake arrangements. More details of the LABRADOR simulation tool can be found in previous work (Alturbeh, 2017) (Alturbeh, Stow, Tucker, & Lawton, 2018).

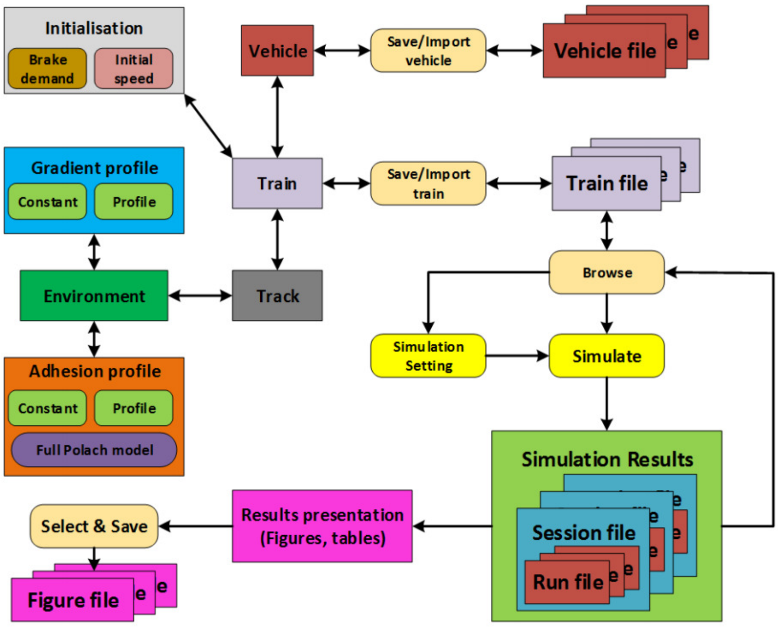

Figure 2 Main LABRADOR model functions (**Alturbeh, 2017**).

The ability to adequately model very low adhesion is critical to LABRADOR, particularly in respect of correctly simulating the behaviour of wheel slide protection systems and estimating the effects on rail head conditioning of successive wheel passes and the application of sand.

Figure 3 shows LABRADOR output compared against measurements for a UK Class 158 two-car diesel multiple unit (DMU) train in dry conditions (BR, 1991) (BR, 1991). In this prediction a Polach approach (Polach, 2005) was used for the creepage - creep force relationship.

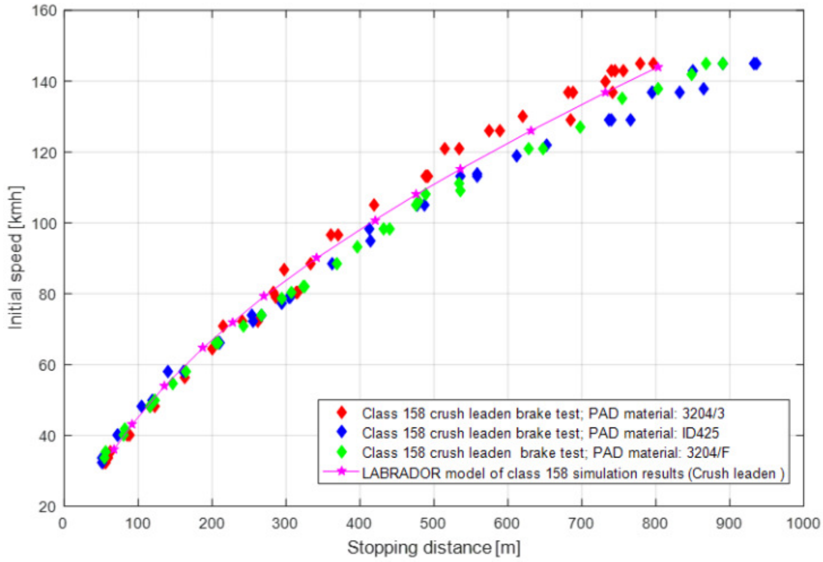

Figure 3 Class 158 full service brake application (notch 3) – experimental and LABRADOR simulation data **(BR, 1991)** **(BR, 1991)**.

Integrating the WILAC model into LABRADOR offers the possibility of significantly improving the modelling of low adhesion in the presence of water and offers the potential for improved understanding of the response of modern braking systems under such conditions.

3 WILAC

The WILAC model was developed to predict adhesion/creep forces in a rolling contact in the presence of water. The model covers the whole range of conditions from dry to damp to wet rail. Special emphasis has been put on low amounts of water in the contact, conditions which may be encountered at the onset of rain for example. The model has been parameterized based on experimental results from a full-scale tram wheel test rig. These results show that adhesion (peak value and characteristic) changes with the water flow rate in a complex way. Adhesion values as low as 0.06 have been observed in the experiments at high creep (see Figure 4) with only wear debris and small amounts of water present in the contact. The model results also agree with experimental data from locomotive tests (Six, Meierhofer, Muller, & Dietmaier, 2015) (recorded at high normal contact force) in dry and wet conditions (see Figure 5). The model may be implemented in multibody software or in braking models to study train performance and braking strategies, especially in damp conditions.

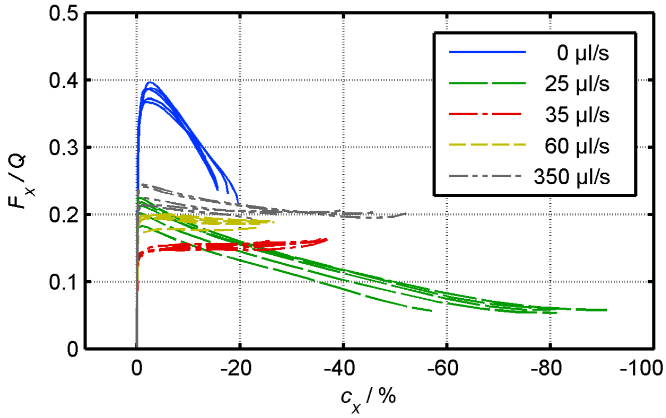

Figure 4 Full-scale experimental creep force curves for small amounts of applied water (**Trummer, et al., 2017**).

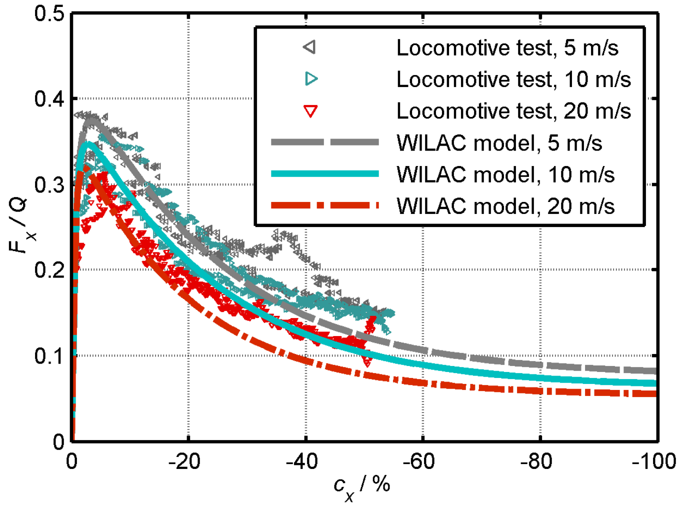

Figure 5 WILAC predictions for wet and dry conditions compared to locomotive test data (**Trummer, et al., 2017**) (locomotive data from (**Six, Meierhofer, Muller, & Dietmaier, 2015**))

4 Implementation of WILAC in LABRADOR

4.1 Approach

Figure 6 shows how the WILAC model has been integrated in the contact patch module of LABRADOR. The integration approach was to keep the modularity of the LABRADOR model and add the WILAC model as a user selectable option. The original Polach model was retained in the contact patch module. A selection functionality has been added so the user can select which model is activated during the simulation.

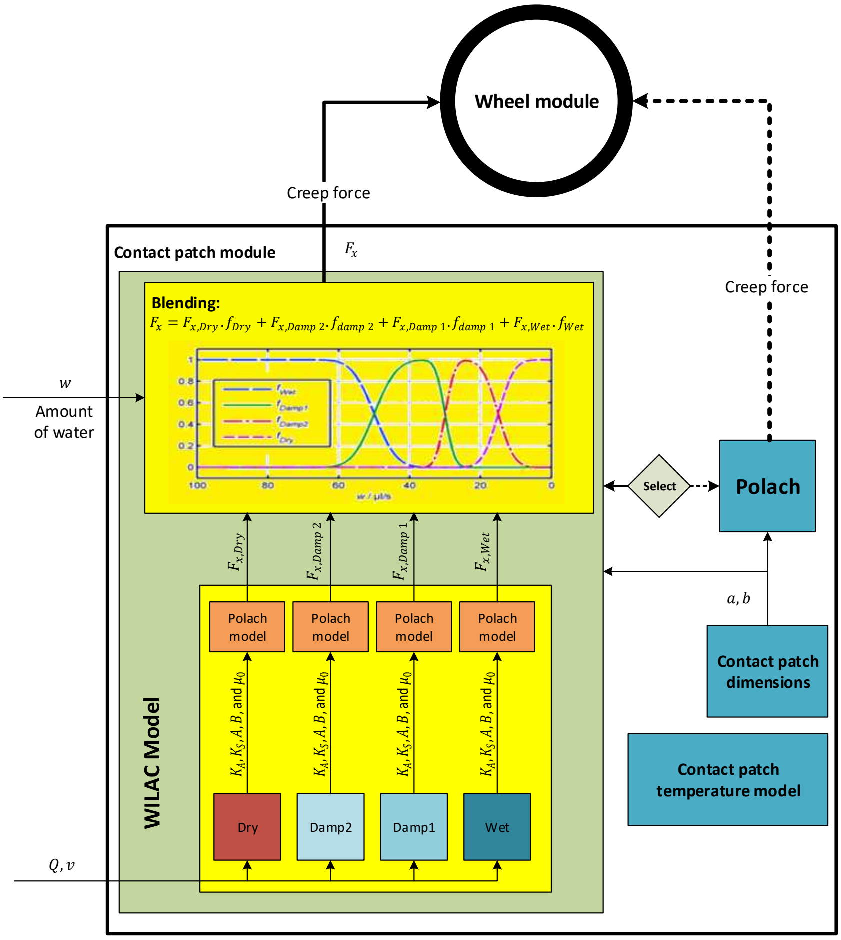

Figure 6 WILAC model integrated into the contact patch module of LABRADOR

The operation of the WILAC model inside the contact patch module can be summarised as follows:

(1) The normal load Q and vehicle speed v are fed to the four predefined contact condition blocks (Dry, Damp2, Damp1, and Wet).

(2) Each block applies multiple linear regression algorithms to calculate the Polach model parameters K_A, K_S, A, B, and μ_0.

(3) The Polach parameters from each contact condition block are sent then to a Polach model to calculate the creep force for each set of parameters. Hence, four creep forces are generated from the Polach model blocks, which are $F_{x,Dry}$, $F_{x,Damp2}, F_{x,Damp1}, and\ F_{x,Wet}$ for Dry, Damp2, Damp1 and Wet condition respectively.

(4) The generated creep forces are then passed to the blending process. The blending process uses the amount of water as input to calculate the weights ($f_{Dry}, f_{damp2}, f_{damp1}, f_{Wet}$) that are applied to each of the four contact conditions. The resulting creep force is then calculated based on:

$$F_x = F_{x,Dry} \cdot f_{Dry} + F_{x,Damp2} \cdot f_{damp2} + F_{x,Damp1} \cdot f_{damp1} + F_{x,Wet} \cdot f_{Wet}$$

(5) The resulting creep force is then outputted and passed to the wheel module.

4.2 Simulation Results

This section presents some simulation results which demonstrate the main differences between the LABRADOR and LABRADOR-WILAC models. All the examples presented below use the 2-car class 158 DMU model. Masses and centre of gravity heights of this train are given in Table 1. Bogie wheelbase is 2.6m, pivot spacing 16m and inter-vehicle pivot spacing 7.208m.

Item	Tare	
	Mass /kg	CG height /m
Car body 1 DMS(A) 57748	26437	1.519
Car body 2 DMS(B) 52748	26677	1.519
Trailer bogie 1	2192	0.56
Motor bogie 2	2005	0.56
Wheelset 1 & 2 trailer	1528	0.42
Wheelset 3 & 4 driven	1925	0.42

Table 1 Class 158 masses and CoG height

The initial speed of train is 20 m/s ($45\ mile/h$) and the driver brake demand is $9\%\ g$ (The brake lever at step 3 or notch 3 position). The case studies cover two rail conditions; dry and damp with 35 $\mu l/s$ of water (Damp1). These conditions represent two of the WILAC experimentally validated conditions as shown in Figure 4.

In this paper, low adhesion is defined as insufficient adhesion to support the demanded brake rate and would normally result in wheel slide and the intervention of the wheel-slide protection (WSP) and/or sanding devices. The level of adhesion shown in Figure 4 cannot be considered as low adhesion as it remains higher than 0.09 for most creepages. However, the Damp2 condition (25 $\mu l/s$ of water) shows a low adhesion level at high value of creepage (e.g. $c_x > 50\%$), but this amount of the creepage will not be occur normal operation and the same condition gives sufficient adhesion for normal brake demands at lower creepage. A scaling factor is therefore introduced to scale the adhesion curve, in order that a sufficiently low adhesion conditions can be generated. The scaling factor is selected to be 0.44 for all cases presented.

The scaling can be justified by the fact that in the experimental work used to develop the creep curves illustrated in Figure 4 no oxide was present at the start of the tests and friction was governed by the presence of water only (iron oxides have to and do develop implicitly during the test). In an actual wheel/rail interface the oxide would be present, either on the rail head or within the contact, and it could be anticipated that the friction would therefore be lower. Nevertheless, this highlights that further work is required to fully characterise the creep-creep force relationship which exist under low adhesion conditions.

Dry condition:

The LABRADOR class 158 model was firstly configured to use the Polach model with a high value of the maximum adhesion ($\mu_0 = 0.3$). In the second run the WILAC model with dry rail condition was used in LABRADOR. The simulation results show that the LABRADOR gives the same results whether the Polach model or the WILAC is selected to generate the creep force. The stopping distance is 202 m in both cases.

Damp1 condition:

The aim of this case is to generate a low adhesion condition and compare the model behaviour when using the Polach and WILAC models.

WILAC model configuration:

A scaled version (scaled by 0.44) of the WILAC adhesion curve of the Damp1 condition is shown in Figure 7 (magenta line). The scaling factor is selected to make the maximum adhesion value equal to 0.07 which is below the adhesion required to sustain a brake demand of $9\%g$. The LABRADOR model was configured so that the water flow rate on the rail is constant at 35 $\mu l/s$.

Polach model configuration:

The default values of the Polach model parameters for low adhesion conditions are given in Table 2. These values are based on the Polach parameters for wet condition (Polach, 2005) except the value of the μ_0 which was selected to give a low adhesion condition scenario.

Polach model Parameter	K_A	K_S	μ_0	A	B
Value	0.30	0.10	0.07	0.40	0.20

Table 2 Polach model parameters in low adhesion condition

This configuration produced an adhesion curve shown in Figure 7 (green line). It can be seen that the Polach adhesion curve (green) decreases dramatically to about 0.03 at 30% of creepage while the WILAC adhesion curve just dropped by 0.01 at the same creepage value. The parameter 'A' of the Polach model represents the ratio between the minimum and maximum adhesion value and therefore controls the drop of the adhesion curve beyond the low creepage peak. The red and blue lines in Figure 7 show the adhesion curves that are generated when the parameter 'A' changed to 0.9 and 0.8 respectively from which it can be seen that the bigger the parameter 'A' the lower the amount of the drop in adhesion curve. The changes in the adhesion-creep curve due to the change of the Polach model parameter shows the sensitivity of the Polach model to the parameter change, which, off course, will be reflected in the LABRADOR behaviour as will be seen in the simulation results below.

These four configurations (WILAC Damp1 and the Polach model with the three configurations of the parameter 'A'), which have almost the same maximum adhesion level, were simulated in LABRADOR. Figure 8 shows the train speed against distance for these four configurations. As can be seen, there are significant differences between the four curves. For example, the stopping distance when the WILAC model is used is about 354 m while it goes up to about 520m with the Polach model default configuration (i.e. A=0.4). However, the stopping distance is reduced when the 'A' parameter increased to 0.8 and reduced further when A=0.9.

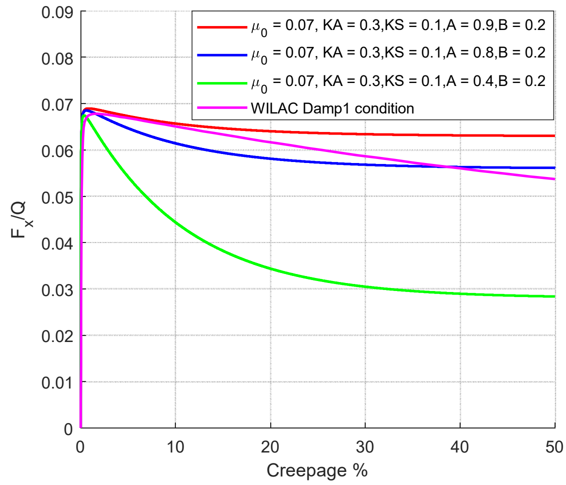

Figure 7 Adhesion creep curve for low adhesion condition using Polach model with different value of the parameter A (red, green and blue) and the WILAC adhesion curve for Damp1 condition (magenta).

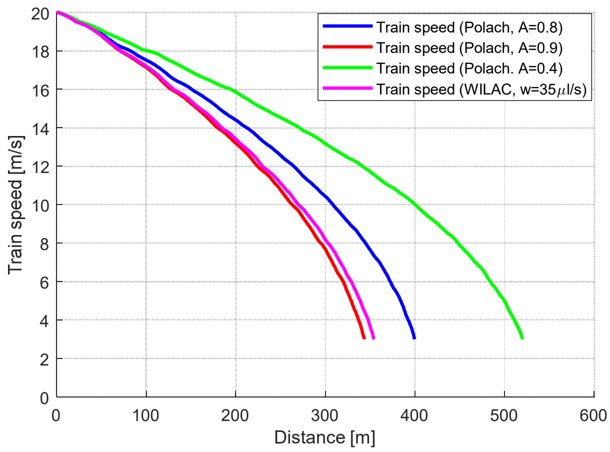

Figure 8 Train speed at low adhesion condition using: Polach model with different parameter A (green, blue, red); WILAC model (magenta)

These differences in the stopping distances are due to the varying levels of the adhesion seen by the wheelsets in the different configurations given in Figure 7. Figure 9 shows the adhesion level at wheelset 1 in Vehicle 1 for each configuration. The fluctuating in the adhesion level is due to WSP activities to maintain the creepage within the configured level. It can be seen that there are clear differences in the shape\behaviour and value of wheelset 1's adhesion for different cases. For example, the adhesion value drops to about 0.03 and remains there for a long distance when the Polach model was used with its default parameters (i.e., A=0.4), the green line in Figure 9. However, increasing the A parameter to 0.8 and 0.9 will change the adhesion shape\behaviour dramatically (blue and red lines). In the WILAC scaled 'damp 1' case, wheelset 1's adhesion level (magenta line) drops slightly for shorter distance. The drop in the adhesion value at higher creepages means smaller wheel-rail force hence slower rotation of the wheelset which further increases the crpeepage value which in turn activates the WSP system that acts to restore the wheelset rotation and decrease the creepage by releasing the brake force on the wheelset. The creepages of wheelset 1 at different scenarios are given in Figure 10.

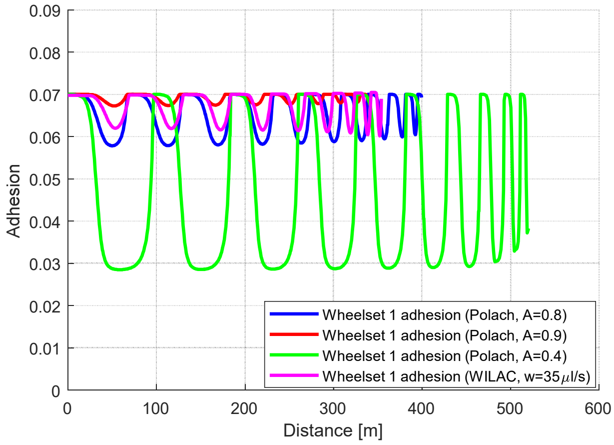

Figure 9 Wheelset1 adhesion at low adhesion condition using: Polach model with different parameter A (green, blue, red); WILAC model (magenta)

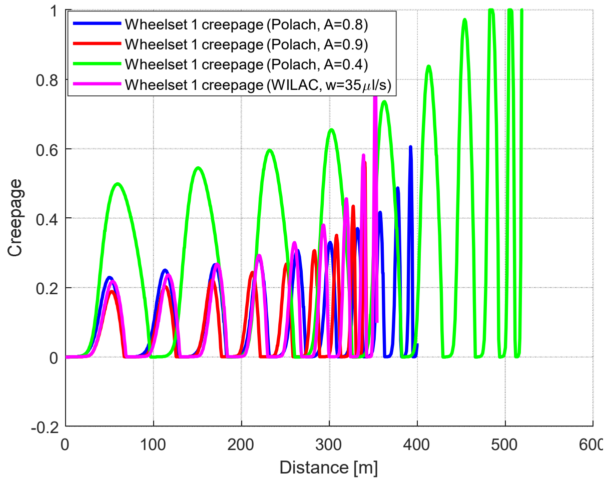

Figure 10 Wheelset1 creepage at low adhesion condition using: Polach model with different parameter A (green, blue, red); WILAC model (magenta)

The activity of the WSP system (and hence the overall braking distance in each case) is also governed by the WSP system model that has been used in LABRADOR and its configuration, thus different WSP models (e.g. more advanced WSP model) or different WSP model configuration will give different results.

The wheel-rail forces are the main variable that effects the train's stopping distance directly. Figure 11 shows the wheel-rail force for wheelset 1 for the different adhesion configurations.

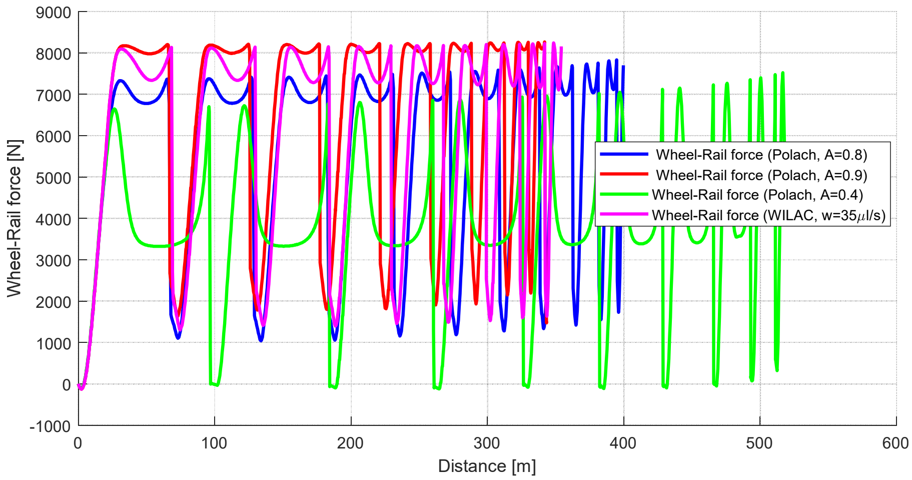

Figure 11 Wheelset 1 wheel-rail force at low adhesion condition using: Polach model with different parameter A (green, blue, red); WILAC model (magenta)

The Polach model (A=0.9) gives the maximum value of the wheel-rail force, thus the minimum stopping distance, while the Polach model (A=0.4) gives the minimum wheel-rail force which drops to zero on many occasions (that explain why this configuration gives the maximum stopping distance). This initial results show that the Polach model is sensitive to its parameters which effect the obtained results significantly.

Additional simulation runs were carried out using the Polach model with different sets of parameters in order to investigate the effect of the Polach model sensitivity to its parameters on the LABRADOR stopping distance results. Table 3 shows the train stopping distance for ten different parameters configurations of the Polach model (the colours of the cells that give the stopping distance are selected to match those in Figure 12).

<table>
<tr><th rowspan="2">Config.</th><th colspan="5">Polach model parameters</th><th rowspan="2">Stopping distance [m]</th></tr>
<tr><th>μ_0</th><th>A</th><th>B</th><th>K_A</th><th>K_s</th></tr>
<tr><td>1</td><td>0.07</td><td rowspan="3">0.54</td><td rowspan="4">0.06</td><td rowspan="10">0.43</td><td rowspan="10">0.35</td><td>388</td></tr>
<tr><td>2</td><td>0.085</td><td>323</td></tr>
<tr><td>3</td><td rowspan="4">0.09</td><td>299</td></tr>
<tr><td>4</td><td rowspan="7">0.2</td><td>309</td></tr>
<tr><td>5</td><td>0.13</td><td>423</td></tr>
<tr><td>6</td><td rowspan="2">0.2</td><td>510</td></tr>
<tr><td>7</td><td rowspan="2">0.087</td><td>511</td></tr>
<tr><td>8</td><td>0.13</td><td>453</td></tr>
<tr><td>9</td><td rowspan="2">0.083</td><td>0.06</td><td>358</td></tr>
<tr><td>10</td><td>0.2</td><td>543</td></tr>
</table>

Table 3 Train stopping distances for different Polach model configurations

It can be seen that the stopping distance differs significantly as the parameters are changed. For example, the difference between the stopping distance for configuration 3 and configuration 10 is about 245 m.

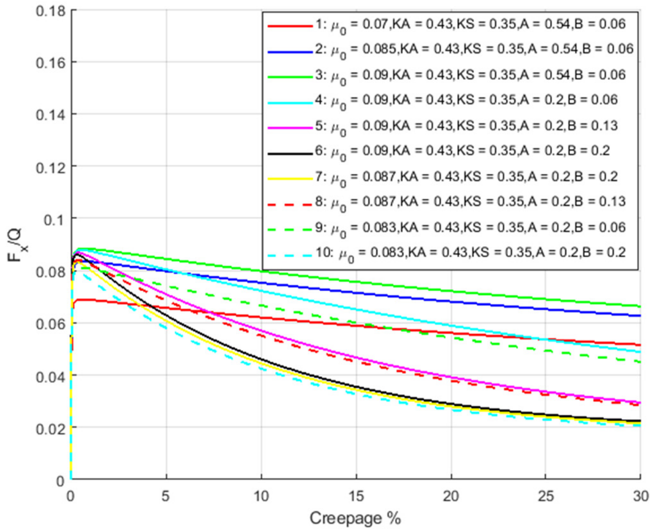

Figure 12 Adhesion creep curves for different Polach parameters configurations (F_x = shear force; Q = normal force)

The adhesion creep curves for these configurations are shown in Figure 12 where it can be seen that configuration 3 (solid green line), which gives the shortest stopping distance, has the maximum peak value and has the maximum average adhesion value over the creepage range, in contrast configuration 10 (dashed cyan line), which gives the longest stopping distance, has a slightly lower peak, but it decreases sharply to give the lowest value of the adhesion at higher creepages (i.e., it has the lowest average value of the adhesion over the creepage range).

The simulation results show that the LABRADOR model behaves differently with different configurations of the adhesion curve model and imply that the same variation in contact conditions would lead to significant differences in stopping distance in real life too. Again, not only the peak friction of the adhesion characteristic (which might be similar for all cases) determines the stopping distance but also the falling adhesion characteristic at higher creepages (average adhesion in relevant creepage range). Using the Polach model to produce the adhesion-creep curve and hence the wheel-rail force, means that LABRADOR will inherit the Polach model sensitivity to its parameters. This means that selecting the wrong (or not precise) parameters will lead to incorrect results. Also the current LABRADOR model assumes that the Polach model parameters are constant which is not the case as the WILAC model shows. For example, Figure 13 shows how the Polach model parameters for the Damp1, Damp2, Wet and Dry conditions in the WILAC model vary as the speed varies. The WILAC model tunes the Polach model parameters dynamically depending on the speed and load, then blends the resulting adhesion creep curves based on the wheel-rail conditions to generate the wheel-rail force. This feature means that users do not have to tune the adhesion model parameters for each condition, instead they only give the rail wetting profile as input and the WILAC model makes the calculation and produces the corresponding adhesion and wheel-rail force based on the train speed, wheel speed, load and the rail condition.

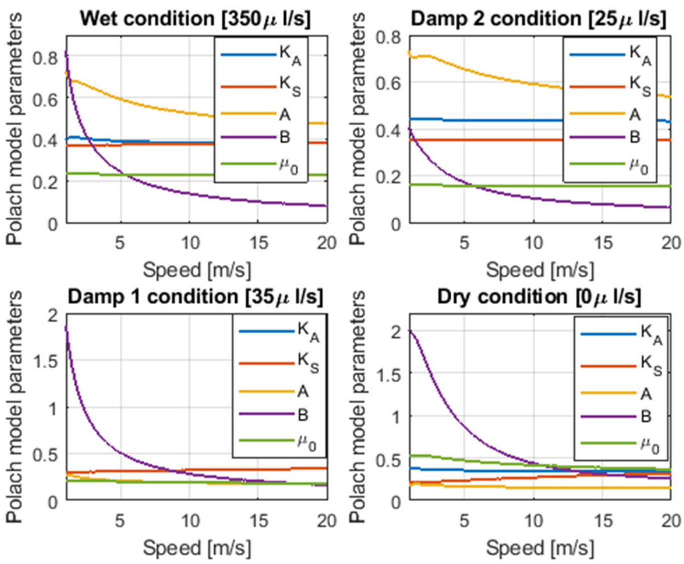

Figure 13 Wet, Damp1, Damp 2 and Dry contact patch conditions' Polach parameter changing during simulation as a function of the train speed

5 Limitations and Future Work

The main limitations of the WILAC model as implemented in LABRADOR are that:

(1) WILAC represents the rail adhesion condition by the water flow rate into the contact in $\mu l/s$. However, water flow rate has limited meaning outside laboratory test conditions and so, an intermediate stage is needed to interpret the users required adhesion input, which could be a linguistic expression of the rail condition into the WILAC water flow rate input.

(2) 'Low adhesion conditions', where the adhesion level is less than 0.09 for notch 3 (9%g) brake demand or less than 0.06 for service brake demand notch 2 (6%g), are generated in the WILAC model by introducing a scaling factor. The WILAC adhesion-creep curves are multiplied by the scaling factor to reduce them to the low adhesion levels required. However, this only resizes the adhesion curve without affecting its shape/behaviour (i.e. the adhesion-creep curve peak position, the slopes of the curve and the position of minimum adhesion value). However, the experimental results presented in (Polach, 2005) and (Buckley-Johnstone, Lewis, Six, & Trummer, 2016) show that the adhesion creep curve shape/behaviour is dramatically changed when the rail condition is changed. It is planned to extend the WILAC model to include low adhesion conditions produced by different environmental factors (e.g. leaf film, grease and lubricant). This would enhance the ability of the WILAC model to represent low adhesion model whilst exploiting the current WILAC methodology using linear regression to produce the Polach model parameters and blending techniques to calculate the wheel-rail force.

6 Conclusions

The validated low adhesion creep force model (WILAC model) has been integrated within a train braking model (LABRADOR model) to enable improved predictions of braking performance for low adhesion conditions resulting from wet-rail syndrome. The developed model would allow range of low adhesion scenarios to be developed and used to optimise brake system performance.

The main advantages of using WILAC model in LABRADOR can be summarised as follows:

- The original LABRADOR model depended on the Polach model for calculation of adhesion -creep curves, which needs a predefined set of parameters. These parameters remained constant during simulation runs. In contrast, the Polach model parameters generated by the WILAC model are a function of speed and load.
- In the original LABRADOR model, the condition of the rail has been categorised in two levels; high adhesion and low adhesion, with each having a set of predefined Polach parameters to generate the adhesion creep curves. However, WILAC provides four models (*dry*, *damp1*, *damp2* and *wet*) that generate four sets of Polach model parameters, based on the speed and load, and by blending these four curves, depending on the rail condition (i.e. water flow rate), the wheel-rail force is calculated.
- It has been found that the Polach model is very sensitive to the model parameters which is reflected in the stopping distances simulated in LABRADOR. However, in WILAC the model itself calculates the Polach model parameters and tunes them depending on the speed and load.

- Any further improvements to WILAC can be integrated easily in LABRADOR due to its modular structure.

It has been shown, that not only the peak friction of the adhesion characteristic (which might be similar for different cases) determines the stopping distance, but also the falling adhesion characteristic at higher creepages (average adhesion in relevant creepage range). Thus, gaining insight into the influence of relevant contaminants on the adhesion characteristic and developing according models are important to improve stopping distance predictions.

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